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The numerical simulation of human phonation

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The human phonation is highly interesting phenomenon, where numerical simulations play an important role due to the practical inaccessibility of the vocal folds. This phenomenon is described by three physical fields – the deformation of elastic body, the complex fluid flow and the acoustics together with mutual couplings. The description and results of fluid-structure interaction (FSI) is here taken from [3] over and this paper focuses on the acoustic part of problem described by the acoustic analogies.

Acoustic domain. Fig. 1 presents a two-dimensional acoustic problem domain. The computational domain, where FSI problem was solved and where acoustic sources are computed, lays between $0 < x < L_{\mathrm{FSI}}$. It is connected with the propagation region (model of vocal tract), far field region and damping PML block. The model of vocal tract is inspired by the MRI data for vowel [u:] from [2].

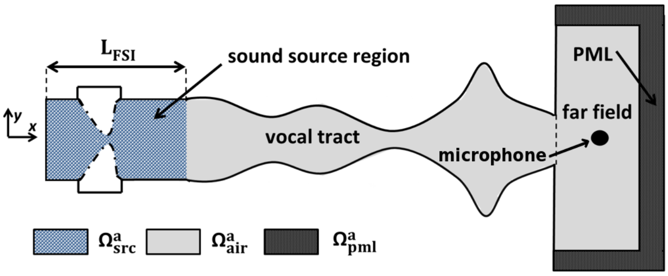

Fig. 1. Scheme of acoustic domain, all walls of acoustic domain are considered as acoustic hard

Lighthill analogy. The propagation of sound described by pressure fluctuation $p' = p - p_0$ is given by inhomogeneous wave equation in the form

$$\frac{1}{c_0^2}\frac{\partial^2 p'}{\partial t^2} - \frac{\partial^2 p'}{\partial x_i \partial x_i} = \frac{\partial^2 L_{ij}}{\partial x_i \partial x_j}, \tag{1}$$

where p_0 and ρ_0 mean stagnant pressure and density, respectively. The sound sources on the right hand side are described by the Lighthill tensor $\mathbf{L} = (L_{ij})$

$$L_{ij} = \rho^f v_i v_j + ((p - p_0) - c_0^2(\rho^f - \rho_0^f))\delta_{ij} - \tau_{ij}^f \approx \rho^f v_i v_j, \tag{2}$$

where following approximation of the Lighthill tensor valid for high Reynold number was used.

Perturbed Convective Wave Equation (PCWE) analogy. This analogy is based on general splitting of fluid flow quantities into mean, fluctuating (non-acoustic) and acoustic (i.e. compressible) parts, e.g., $p = \overline{p} + p_{ic} + p_a$. Supposing irrotational acoustic field leads to the equation

$$\frac{1}{c_0^2}\frac{D^2\psi^a}{Dt^2} - \Delta\psi^a = -\frac{1}{\rho_0^f c_0^2}\frac{Dp_{ic}}{Dt}, \tag{3}$$

where the acoustic potential ψ^a related to the acoustic particle velocity $\mathbf{v}^a = -\nabla\psi^a$ and pressure $p^a = \rho_0^f \frac{D\psi^a}{Dt}$ is sought. Symbol $\frac{D}{Dt}$ denotes the substantial derivative, i.e., $\frac{D}{Dt} = \frac{\partial}{\partial t} + \overline{\mathbf{v}} \cdot \nabla$. For further details see [1].

Numerical model. The acoustic analogies (1) and (3) were discretized in space by the finite element method and in time by the Newmark method. For implementation details see [3].

Sound sources. The computed sound sources in the form of right hand terms in Eq. (1) or (3) were analyzed by Fourier transform. The results show that main sound sources of frequency 232 Hz is located inside the glottis. The sources of higher frequency like, e.g., at 2486 Hz are mostly distributed in the channel behind the glottis, see Fig. 2.

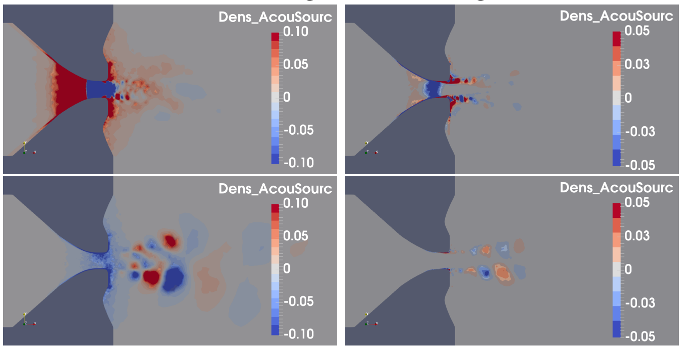

Fig. 2. The computed normalized sound source densities at 232 Hz (upper panel) and 2486 Hz (lower panel). Left are results for PCWE analogy, right for the Lighthill analogy, respectively.

Sound propagation. The computed sound sources are used as input for time solution of chosen acoustic analogy. The frequency spectra of the acoustic pressure monitored at the microphone position outside the mouth is shown in Fig. 3. The resulting peaks in frequency domain exhibit qualitatively good correspondence with the frequencies of first three formants 389 Hz, 987 Hz and 2299 Hz measured for the vowel [u:] in [2], marked in Fig. 3 by black lines.

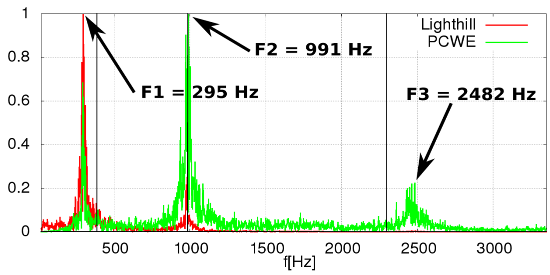

Fig. 3. The Fourier transform of acoustic pressure obtained by Lighthill and PCWE analogy

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